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The effects of snowfall on the transmittance of visible, infrared, and millimeter radiation are assessed on the basis of currently available information. From a tactical applications viewpoint, little information is available for millimeter wavelengths; and for the visible and infrared, results vary widely. This variance appears to be real and due to two effects: the variety of snow types and the coincidence of fog.

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20. ABSTRACT (cont)

Empirical formulae relating transmittance to snowfall intensity are found but are judged to be less useful for tactical purposes than relations to visual range. For the latter, results from different investigators must be combined. Such empirical formulae are thus derived for wavelengths 0.63µm, 3.5µm, and 10.6µm; and while considerable uncertainty is evident, apparently practical boundaries can be established. Lines of approach for future experimental work are also identified.

An increasing number of Army systems rely critically on the propagation of optical energy through the atmosphere. As a result the demand for reliable estimates of optical attenuation in low visibility aerosol conditions is steadily increasing. Among those attenuation least observed or measured is that of snowfall.

CONTENTS

INTRODUCTION

The effects of snowfall on the propagation of light are of interest to the military community because of the increasing number of imaging, tracking, and detecting devices which rely on light propagation. The wavelengths of interest extend from the visible to the millimeter region. The work reported here is part of a larger effort devoted to the modeling of atmospheric effects on electro-optical systems for both design planning and deployment. The object of that effort is the production of a library of computer codes capable of describing adverse environmental effects, both natural and man-made, as they relate to readily observable meteorological parameters. One of the more difficult conditions to so describe is snowfall.

The effects of snowfall are more varied and generally more severe than rain. Over a sizable portion of the earth, snow occurs frequently enough to be a potential hazard to operations. As an example, at Montreal (latitude 45°) over 200 hours of snowfall were observed in one winter season by Warner and Gunn [1]. Durations of snowfall of several hours are common in such areas. Thus an ability to estimate the propagation effects can be an important factor.

The purpose of this work has been to determine from available data what the magnitude of attenuation by snowfall is, what the contributing factors are, and what parameters are required for its estimation. Sufficient data have not yet been acquired for millimeter wavelengths; however, the nature of millimeter attenuation effects can probably be anticipated from size distributions.

More information is available for the visible and infrared (IR) regions, and certain features immediately become evident from this information. First, the magnitude of attenuation is large--lying between the magnitudes for fog and rain--but this depends on the wavelengths. Second, every snowfall is different; attenuation varies widely, depending on snow type, temperature, humidity, and other factors. Finally, since most of the accessible data on snowfall were obtained with effects other than propagation considered, all of the necessary information is seldom available.

BACKGROUND

Before specific measurements are discussed, the nature of the problem will be considered. In snowfall the major effect on propagation is scattering. Conventionally this effect is treated successfully by assuming spherical scatterers and describing their sizes and optical properties. With snow, such an approach is not possible because of the irregular shapes of the particles, at least until wavelength λ is large enough so that particle diameters are much less than λ. This generally means $\lambda > 10$ mm. The only alternative for shorter wavelengths then is empirical determination.

Scattering by snow particles is not the only important effect and may often be rivaled by scattering from fog droplets accompanying the snow. This phenomenon appears to be less well recognized, and many of the existing observations are difficult to assess because they do not mention it. Since the presence of fog in snowfall is difficult to detect and still more difficult to measure, the frequency of occurrence of this problem is not known. As will be seen later, the presence of fog is probably the rule rather than the exception, at least for some locations. Haze or other particulate materials may also accompany snow.

A smaller but not negligible effect is due to water vapor. Except near absorption bands, this effect may be more indirect as it affects the properties of accompanying haze. In at least one case [1], it is noted that attenuation at 0.45μm increases with humidity, becoming quite significant for relative humidity above 85 percent. Its significance at wavelengths near absorption bands is obvious, and appropriate absorption calculations may be warranted. However, generally the scattering is expected to far outweigh absorption.

The following paragraphs summarize existing data and give a synopsis of the results. The difficulties in obtaining suitable measurements in snow are pointed out; and as a starting point, a "typical" snowfall is described. An attempt is made to identify meteorological observables which are readily obtainable and which may be used to establish transmittance predictions.

AVAILABLE MEASUREMENTS

Lillesaeter [2], Mellor [3], Warner and Gunn [1], Zel'manovich [4], and Polyakova and Tretjakov [5] have measured light attenuation in snowfall. These results are difficult to compare directly because of differences in their apparatus and in the way the data are related to snowfall rate. Each result, however, gives an empirically derived equation relating either extinction coefficient or visibility to snow amount, and an attempt has been made to convert these results to similar units without loss of accuracy. The resulting equations are given in Table 1.

Also included in the table is a visibility relation presented by O'Brien [6] who reports this relation in the form of extinction coefficient. O'Brien measured visibility, converting by means of the Koschmieder relation which is doubtful for snowfall; therefore, his extinction coefficient is given only in terms of visibility. Figure 1 gives plots of these relations where the disparity of results is evident.

All of the measurements were made at visible wavelengths except for those of Zel'manovich [4] in which a 3.87μm source was used. All of the measurements represent observations over one or more winter seasons, again excepting those of Zel'manovich which represent a single snowstorm. While all researchers are careful to measure the rate of accumulation, little note is taken of the presence or absence of fog, and temperature and relative humidity are not reported. O'Brien [6] refers

TABLE 1. TRANSMITTANCE ALGORITHMS FOR SNOWFALL

Investigator	Extinction Coefficient (km^{-1})	Visibility (km)
Lillesaeter	$\alpha = 3.93\ R$ *	$V = R^{-1}$
Zel'manovich	$\alpha = 1.3\ R^{0.5}$	
Polyakova and Tretjakov	$\alpha = 3.2\ R^{0.91}$	$V = 0.94R^{-0.91}$
Mellor	$\alpha = 1.11\ R^{0.42}$	$V = 1.65\ R^{-0.42}$
Warner and Gunn	$\alpha = 2.53\ R$	
O'Brien	$\alpha = 1.393\ R^{0.69}$	$V = 1.25\ R^{-0.69}$

*Accumulation rate, R, is mm hr^{-1}. Dashed line indicates primary measurement.

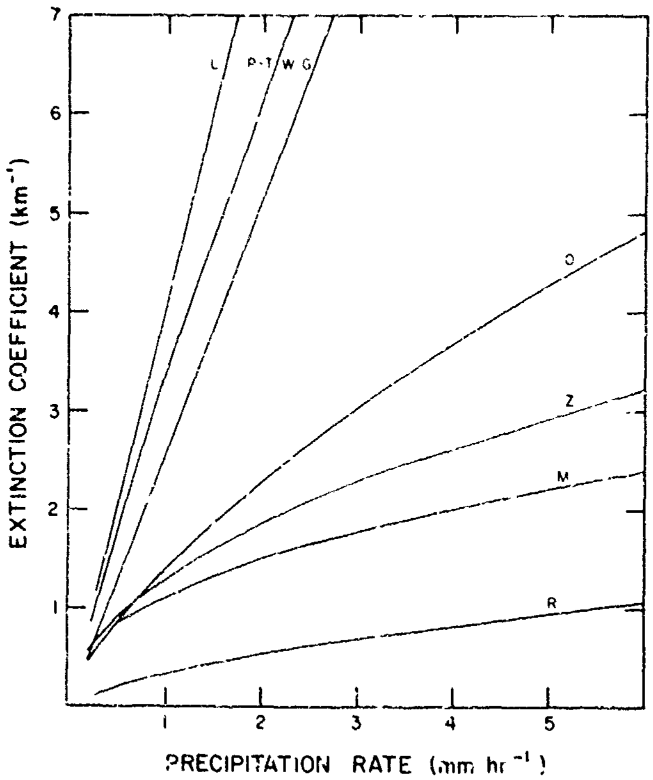

Figure 1. Snowfall attenuation coefficients versus precipitation rate as obtained from several published empirical studies. All are for visible wavelengths except (z) which is for 3.87μm. R denotes the case for rain.

to the frequent presence of fog with snow at his site at Hanover (also the site of Mellor's work) and Warner and Gunn [1] mention the effect of high relative humidity (but not fog), suggesting that it may account for almost 50 percent of the observed attenuation.

Careful observations of snow type were made only by Mellor [3], who does not break down his transmittance data by type, and O'Brien who does, but who, in addition to the earlier mentioned difficulty, presents his results in terms of area concentration which can be converted to accumulation rate only with knowledge of the size distribution. Mellor observes that the proportionality constant relating V and α is a factor of 2.25 less than that of the Koschmieder formula, that is, $\alpha V = 1.74$. This affects O'Brien's results as mentioned above.

The importance of temperature is evidenced by studies of visibility [7,8, and 9] and by transmittance-based snow rate measurements [10], which show attenuation to be significantly lower in melting snow. Rain represents a limiting case. Zel'manovich, however, measured a temperature well below freezing for his case so that other factors can also depress the curve. At this point no clear reason for the dispersion of results can be identified.

To see the magnitude of the effect, a rate of 1 mm hr^{-1} may be considered. According to [3], α is 1.1 and the transmittance over 1 km is 33 percent. According to [2] α is 3.93 and transmittance is 2 percent, making a difference of a factor of 17. From [1] which is presented as an improvement over [2], the value is 8 percent, still down by a factor of four, and the disagreement increases with increasing R.

Mellor's results include numerous observations in a total of 16 snowfalls with comments about the snow type and particle size. Figure 2 shows results derived from his report with the reciprocal of visibility plotted against snow rate and indicating different snow types. No clear correlation with type is evident, but the spread of the data indicates that factors other than R affect the extinction. Mellor notes that these observations were limited to widespread dry snowfalls of 1 hour or more duration. Wet snow would be expected to produce results to the lower side of this grouping.

Lillesaeter [2] measured transmittance at 0.45μm, but reports that visibility, V, is equal to 1/R although he does not show data for V. The information as reported by Lillesaeter leads to the result, $\alpha V = 3.93$.

Warner and Gunn [1] also measured transmittance at 0.45μm and concur with Lillesaeter in the relation of V to R. Thus, from them we obtain $\alpha V = 2.53$. Again no data for V are presented, and it is assumed that the two variables were not observed simultaneously.

Polyakova and Tretjakov [5] report measurements of both variables but do not tabulate the data. They do, however, present empirical relations for both in terms of R from which $\alpha V = 3.01$ can be obtained.

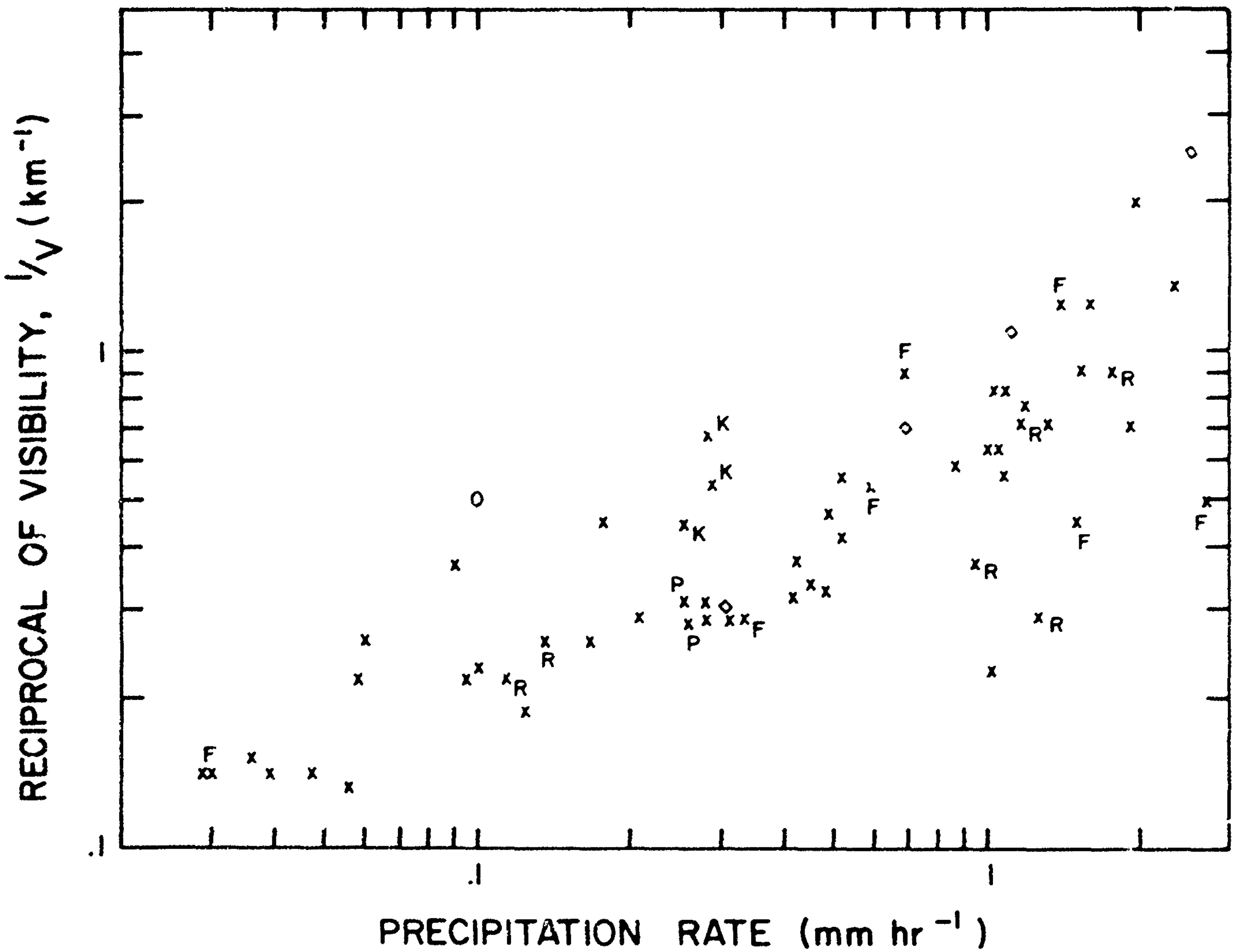

Figure 2. Reciprocal of visual range versus precipitation rate for snowfalls during 1964-1965 as observed by Mellor (1966). Also shown are results from Lillesaeter (1965) (◇) and Zelmanovich (1960) (o). Letter designations refer to rimmed (R), large flakes (F), dendritic (Y) forms, and pellets (P).

Both Mellor and O'Brien [3,6] measured visibility by means of contrast attenuation at two visible wavelengths. However, only Mellor provides a relation between α and V based on actual measurements. He obtains $\alpha V = 1.74$.

These different results are plotted in Figure 3. The results [5] and [1] are considered most representative for the visible wavelength region.

Chu and Hogg [11] measured transmission losses in light snowfall at 10.6μm, 3.5μm, and 0.63μm. The indicated points in Figure 4 were obtained from their results and by use of their measurement at 0.63μm to derive V via the formula obtained from Polyakova and Tretjakov [5].

By approximate fitting to this data, relations can be obtained for the extinction at 3.5μm and 10.6μm in terms of visibility. These relations are:

$$\alpha_{10.6} = 3.5V^{-0.8} ,$$

$$\alpha_{3.5} = 3V^{-1.2} .$$

Note, however, that Chu and Hogg's result did not always indicate consistent behavior. Most of the time attenuation at 0.63μm exceeded that at 3.5μm although occasionally the reverse occurred. This could be explained on the basis of an accompanying light fog of varying size distribution.

Sola and Bergemann [12] have reported broadband measurements of transmittance in snowfall for the 3-4μm and 8-12μm regions. Their data were obtained in tests at Fort A. P. Hill, Virginia, and Grafenwöhr, West Germany. In presenting their results, they use values of visibility that are derived from near IR extinction coefficients by means of the Koschmieder formula, $\alpha V = 3.91$. Since, from the work already discussed, that formula appears to be inapplicable in snowfall, their results are recalculated by using the formula obtained from Polyakova and Tretjakov [5] (Figs. 5 and 6).

By curve fitting to these results, slightly different relations are found for the IR extinction than from the data of Chu and Hogg [11]. Here the relations are

$$\alpha_{3.5} = 3.3V^{-1} ,$$

$$\alpha_{10.6} = 4V^{-1.1} .$$

When all of these data are combined and fitted, the resulting formulae are

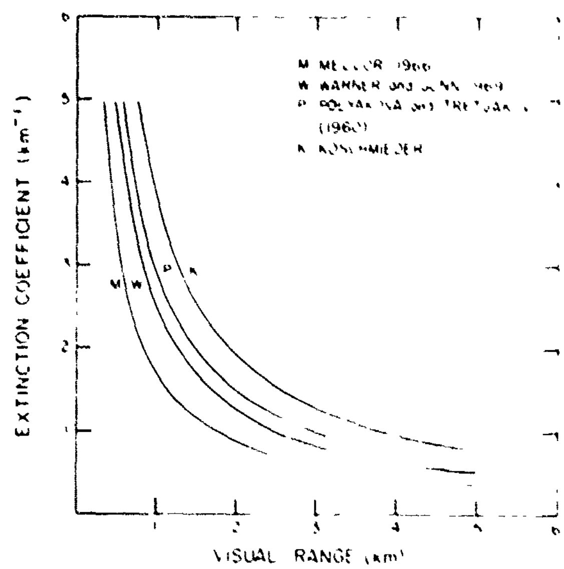

Figure 3. Empirical formulae for extinction versus visual range as derived from the results of Polyakova and Tretjakov (1960), Warner and Gunn (1969), and Mellor (1966). Koschmieder's formula is shown for reference.

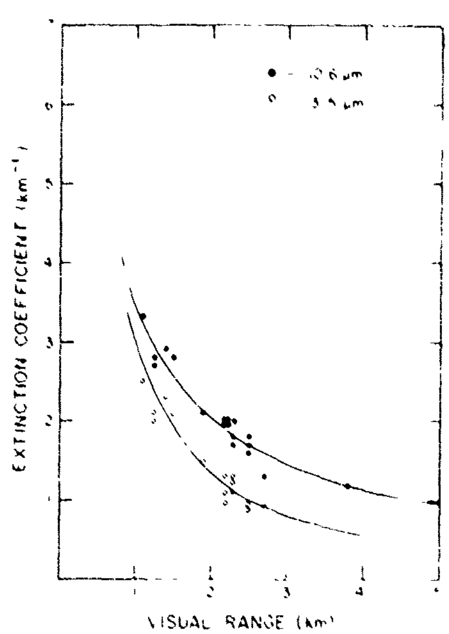

Figure 4. Extinction at 3.5μm and 10.6μm measured by Chu and Hogg (1968) in snowfall plotted versus visual range as obtained from their simultaneous measurement at 0.63μm using the relation derived from Polyakova and Tretjakov (1960). Formulas for fitted curves are given in text.

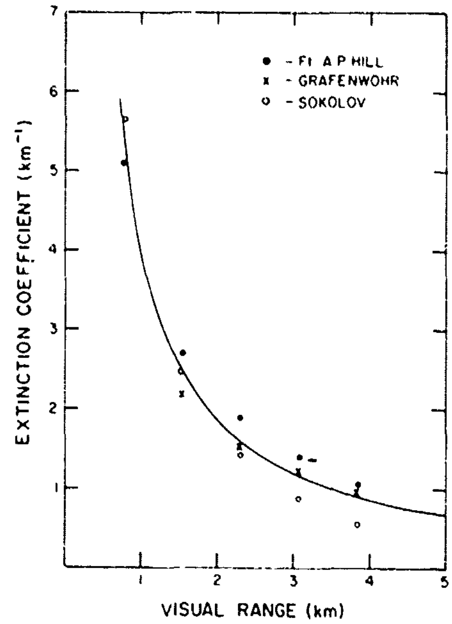

Figure 5. Extinction at 10.6μm versus visual range from Sola and Bergemann (1977) corrected according to Polyakova's results (see text). These authors also present results from Sokolov (not available to this author).

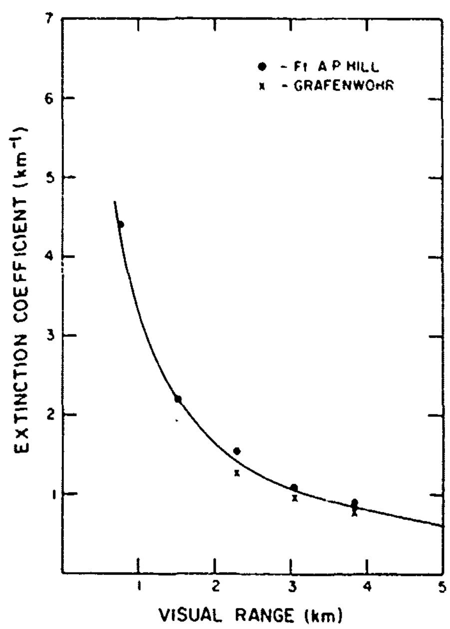

Figure 6. Extinction at 3.5μm versus visual range from Sola and Bergemann (1977) (obtained at Ft. A. P. Hill, Virginia, and Grafenwöhr, West Germany) corrected according to Polyakova's results (see text).

$$\alpha_{10.6} = 3.8V^{-0.[illegible]} ,$$

$$\alpha_{3.5} = 3V^{-1.1} .$$

Recent work reported by Muench and Brown [13] appears to be consistent with these findings.

Graupel results from the accumulation on the snow particles of supercooled cloud droplets as they fall, to the extent that they become roughly spherical [10]. This phenomenon is common with deep cloud systems and particularly at sea or near large bodies of water when moisture content is high. Attenuation is much less for graupel than for other forms for an equal precipitation rate because of the increased density of the particles. However, the relationship to visibility may or may not be significantly affected.

Dendrites and spatial dendrites are the star-like forms usually thought of (and photographed) as typical snow particles. They are not, however, the most common form. They occur most often in weak storms or at the extremities (temporal and spatial) of heavier storms [14]. They clump together easily and tend to produce large agglomerations that break up easily. Their effect on propagation is often among the most severe for unit intensity of precipitation because of their very low effective density. Reliable estimates of their attenuation coefficients are the most illusive, however, because of their clumping tendency which can reduce the number concentration and therefore the attenuation.

The most common form of snow particle is the aggregate, probably because it is produced by the most common forms of winter snowstorms. It is associated with widespread steady snowfalls from stratocumulus or nimbostratus systems in which there is an abundant supply of moisture. Thus it may be less common in dryer regions. Size distributions for aggregates are more well-behaved and better understood so that propagation can probably be best described for them. Also more data appear to be available for aggregates; therefore, they will be considered representative of a typical snowfall.

Table 2 lists other characteristics that describe the typical snowfall with the qualification that the probability of departure is fairly high. These characteristics might be expected to apply to winter polar cap regions or those latitudes that are snow covered in winter but not in summer. The data of Table 2 are intended as a starting point for describing snowfall attenuation; important modifications and departures from them will be discussed later.

Size distributions for snowfalls consistent with Table 2 are presented in Fig. 7. These distributions are due to Gunn and Marshall [17], Sekhon and Srivastava [15], Litvinov [16], and Zel'manovich [4], and represent snowfalls of approximately 0.1 mm hr^{-1} intensity. Of these researchers, only Litvinov actually measured the snow particles. The others measured melt stains left by the particles and described the size distribution of the equivalent water droplet.

TABLE 2. TYPICAL CHARACTERISTICS

Type	Aggregate of 10 to 100 crystals
Intensity	< 1 mm hr^{-1} 80% of time
Size Range	Peak at 0.1 to 1 mm, 90% $<$ 2 mm
Concentration	1000 m^{-3} (1 ℓ^{-1})
Visual Range	1.5 km

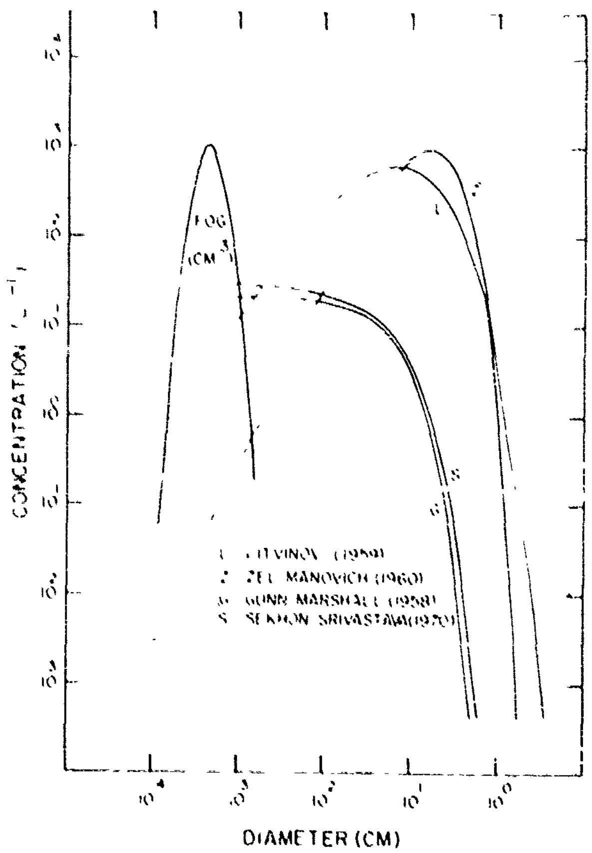

Figure 7. Snow particle size distribution functions proposed by various investigators. A distribution typical of fog (note different units) is shown for reference.

Zel'manovich observed an approximate ratio of the snowflake size to that of the stain (9:10) and also that of stain to the droplet diameter (4:1) to obtain an appropriate ratio (4:1.1) for relating droplet size to flake size. The curves plotted here have been obtained by applying this ratio to his distribution as well as those of [17] and [15].

The distributions of [17] and [15] are not realistic in the small extreme and are represented by their authors as applicable only above 0.1 cm. Even so they appear to fall too sharply toward larger sizes to be representative of aggregates for which they are intended, indicating that a different correction factor may be applicable to them.

The curves Z and L in Fig. 7 both show peaks in the vicinity of 1 mm, as expected, and are relatively broad. Zel'manovich observed flakes as large as 0.7 cm in obtaining his data (single snowfall). Litvinov's results are based on 172 photographs of falling particles obtained throughout one winter season. Both use modified gamma functions of the generalized form

$$N_d = C\, d^{\alpha}\, e^{-\beta d}$$

in which N_d is number of particles of diameter d per unit volume per unit size range, C is a constant, and α and β are the distribution parameters. Note that β = 2/(modal diameter), while α is inversely related to the width of the distribution. Litvinov reports that α decreases as temperature increases, thus broadening the distribution. This seems consistent with Zel'manovich's results which were obtained under relatively cold (-4.6°C) conditions and show a narrower distribution.

These distributions show that visible and IR wavelengths are much smaller than the particles of snow; therefore, very little wavelength dependence of scattering would be anticipated. At approximately 1 mm, more severe effects due to resonance can be expected. Note that the distributions are highly variable at times, and those shown here are based on averaged data, taken in steady snowfalls. When snow consists of powder, needles, or pellets, or is in arctic regions, a shift to smaller sizes is expected.

It is also important to note that snow is often accompanied by fog which has a smaller size distribution as shown. The effect on visible and IR wavelengths is significantly increased in this case. Estimates of the magnitude of fog are not available from the data since the presence of fog is not reported. One reason may be the difficulty in seeing fog in a snowstorm.

CONCLUSION

The propagation of light in snowfall as it is represented by existing experimental data has been discussed. The wide variation in the results

found is evidently caused by two factors: the many different forms of snow and the coexistence of fog particles. The available data are not sufficient to permit the presentation of results separately for each snow type, and the effect of fog can be treated only generally.

Scattering is easily the most significant mechanism of attenuation throughout the visible and IR and, probably, most of the millimeter wave regions. Water vapor absorption, next in importance, becomes appreciable only near absorption bands.

On the basis of size distributions, attenuation by snow particles alone can be expected to increase for wavelengths closer to the range 0.1 to 10 millimeters. In that range, maximum attenuation is anticipated. Thus, at 10.6μm, which in haze propagates better than visible wavelengths, the attenuation by snowfall will be more severe than for visible.

Inconsistent experimental results for 3.5μm are considered indicative of the presence of fog. From the small amount of data available, the following relations for extinction in terms of visibility are obtained, applicable to the range of V from 1 to 5 km.

$$\alpha_{0.63} = 3V^{-1}$$

$$\alpha_{3.5} = 3V^{-1.1}$$

$$\alpha_{10.6} = 3.8V^{-0.95}$$

Results at 1.06μm are expected to be very close to those at 0.63μm. A generalization in terms of wavelength cannot be made without further data. In particular, correlations are required with relative humidity for the ranges above and below 85 percent to assess fog effects. Correlations with temperature and in some ways with snow type (possibly through cloud conditions, geography, etc.) are required to specify the snow effects.

The expression of extinction in terms of observables other than visibility is not yet feasible. The most likely "other observable" is snow rate expressed either as area concentration (cm^2 per m^3) or accumulation ($mm\ hr^{-1}$) for which expressions are possible. However, dependence on snow type then becomes more critical and this observation is not practical in a tactical sense. What is needed as an alternative to visibility is a theory yielding extinction in terms of meteorological parameters such as temperature and relative humidity. Such a theory would have to be based on more accurate models of snowstorms than currently exist. Work toward this may be warranted, however, by the fact that it offers the potential for forecasting optical effects.

From the results discussed in this paper, a general statement can be made that attenuation will be greater when snow is dryer (colder) and that the peak in such cases will be shifted toward the lower side of the 0.1μm to 10μm range (wavelength). The presence of fog will significantly affect near IR wavelengths perhaps out to 10μm. Values of α for "typical" storms are:

visible to 3.5μm	$\alpha = 2\ km^{-1}$
10.6μm	$\alpha = 2.53\ km^{-1}$

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